SPACECRAFT ATTITUDE CONTROL USING STAR FIELD TRACKERS

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ABSTRACT

This paper describes a "maturing" class of attitude sensors used to determine spacecraft attitude with respect to the celestial sphere. During the past fifteen years, the design direction of attitude sensors has turned towards star field trackers and away from single-star trackers. The focus of this paper is on the description of the principles of operation and processes by which these star field trackers recognize and track a desired star field.

1. INTRODUCTION

To maintain a healthy space program within current budgetary constraints, the American National Aeronautics and Space Administration (NASA) has mandated that the design direction of space equipment and spacecraft must change. The total costs of a space program, including the mission operations costs, must be drastically reduced. To achieve this goal, the following was recommended: Equipment and spacecraft must be made smaller-- by an order of magnitude- to reduce launch costs which are very weight-dependent. Guidance equipment, scientific instruments, and spacecraft bus systems must be made autonomous so that no, or very little, control is needed from the ground. Since mission operations personnel costs on a long-duration mission can equal the space project design and launch costs, autonomous operation is an important goal. Also, where possible, equipment should be multi-purpose serving a spacecraft control function and a scientific function, or several scientific functions.

As beneficiaries of the advances in computer technology and electronic microminiaturization, attitude sensor system designers have been able to meet all of the NASA goals. Weight and volume of present attitude sensors have been reduced by more than an order of magnitude and are continuing to be reduced as CCDs and other solid-state sensors become more and more efficient in detecting energy. Reliability has increased primarily through the use of mass-produced integrated circuits, reducing the parts count in reliability calculations. Through the use of modern spacecraft computers with huge memories and with new star field recognition algorithms and programs, autonomous guidance and attitude control operation has been achieved.

2. BACKGROUND

In the 1960s and 70s, most spacecraft attitude knowledge and control came from the use of sun trackers and star trackers. Just about all of these attitude sensing devices used photomultiplier tubes, image dissectors, and phototubes as the star sensor. Requiring high voltage supplies to operate, requiring special packaging and mounting to protect the glass envelopes of these tubes, and having no energy integrating capability, these devices were far from ideal, but they were the best available at the time. Due to the difficulty of containing high voltage in Space and preventing arcing, and the difficulty in packaging these glass-envelope tubes so they would not crack or break during launch, instruments using these tubes had a lower reliability figure than almost all of the other electronics instruments and Systems.

In the early 1970s, charge-coupled devices (CCDs) were invented. At JPL, the development of spacecraft star trackers and optical navigation devices using CCDs as the sensor, began in the mid 1970s. In 197s, W. Goss of JPL described the advantage CCD trackers should have over image-dissector star trackers, the predominant type of tracker at that time. Goss identified the outstanding advantages of CCD sensors: dimensional stability, geometric and photometric linearity, high quantum efficiency and signal integrating ability, providing intrinsically high signal-to-noise ratio, usc of low operating voltages, small size, and insensitivity to magnetic fields. All of these characteristics could contribute to a smaller tracker which could measure and track astronomical objects with more accuracy than the presently used large image-dissector trackers. Early breadboarding of CCD trackers at JPL[2] and elsewhere demonstrated the superior pointing accuracies that could be achieved with CCD sensors, with calibration accuracies approaching 1/100th of a pixel.

in the early 1980s, an Advanced Star and Target Reference optical Sensor (ASTROS) was proposed by Dr. Richard H. Stanton of the Jet Propulsion Laboratory (JPL)[3]. 'l'he goal was to build a complete star tracking system using a CCD as the sensing clement to verify the superiority of the CCD over image-dissector trackers. Looking ahead to all of the future space missions in which JPl, was involved, and the mission-unique requirements that would be placed on an attitude control and tracking sensor, it was decided to develop an instrument which could track a star field as well as a single star. in many missions, it is difficult to know, initially, the spacecraft's attitude in space with respect to the celestial sphere, by looking at only one star. Star magnitude alone is not a dependable means of recognizing most stars. A star field is far more easily recognized and has relationships, such as angular separation between stars as well as individual magnitudes, that make the star field mom unique. Also, tracking the positions of several stars is inherently more accurate. than tracking the position of a single star. The image of a single star can cause larger pointing errors than the average pointing error of several star images in various areas of the field of view. Also, looking towards the future, recognizing star fields gives the capability for autonomous attitude control, almost impossible when tracking only one star.

3. THE PROBLEM

Recognizing a star field, when looking at a portion of the celestial sphere with dozens of stars, is not easy. Tracking many stars and generating signals representing the error between where they arc imaged and where they arc desired to be imaged, requires very special logic. When recognized, special algorithms arc required to find the centroids of the star images. The J2000, or some other coordinate system, of the position vectors of the star images must be known to determine spacecraft attitude. All of these operations involve an instrument far more complex than the "simple" star trackers used in the past for spacecraft attitude determination. The problem is to design such an instrument which is ultra-reliable, small, low powered, lightweight, and has the memory and logic to perform all of the functions described above.

4. SOLUTIONS

Most star field trackers today arc video cameras with CCD sensors and with computers to perform control, recognition, tracking, and attitude determination. The video output from the camera is digitized and goes to a special purpose or spacecraft central computer. Computer programs, through video thresholding schemes, limit the number of stars in a field that will be processed. Stored in the computer memory is a star catalog with the celestial coordinates of each star, in some reference system, that will be used for star field recognition. The angular distances and other parameters describing the stellar relationships arc stored also. When a star field is imaged, its angular relationships and identifying parameters arc computed and compared to the data base in the star catalog. When there is a match, the computer outputs the celestial sphere coordinates of the spacecraft attitude.

The development of star field trackers is given by describing three "solutions," from one of the first to fly to the most current.

5. ASTROS STAR TRACKER (AST)

The AST that was built at JPL had the performance characteristics shown in Table 1. The first use of the AST was on the Space Shuttle as part of the Astro missions for ultraviolet astronomy. The AST was part of the Astro Mission Image Motion Compensation System (IMCS). This system stabilized the target images of two of the three telescopes by sending error signals to movable mirrors in the optical paths of the telescopes. The three telescopes and the AST were mounted on an Image Pointing System (IPS) gimbaled platform which had its own star trackers, called the optical Sensor Package (OSP), for acquisition and tracking.

The design of the AST was driven by the requirement to make image displacement measurement to sub-arc second accuracy. The field of view was made small to increase the AST angular sensitivity. As a consequence, the aperture was made large, 100mm, to have enough light collection ability to sense a very large range of star magnitudes so there would always be at least one star in the small field of view no matter where the AST was pointing. Since mechanical stability was absolutely essential over the varying ambient temperature range of the shuttle flight, Invar was used liberally in the optics-CCD housing. Electric heaters and a thermoelectric cooler were used also, all to minimize the effects of temperature changes. Though heavy and power hungry, all of these design features worked very well and the AST performance met its stability requirements.

The IPS was aimed at the desired star fields by the on-board astronauts entering a target catalog identification number. The catalog entry contained the celestial coordinates of the target. Using the IPS gyros as inertial reference, the IPS was pointed at the target position. The OSP reduced the target position error to less than 10 arc seconds.

To acquire up to three guide stars, the AST scans its field of view, determined by the IPS pointing direction, at each of 16 threshold levels available, starting with the highest. A programmed signal integration time for the CCD, related to the signal level of the brightest star imaged, is selected to optimize the star. position measurement accuracy. The guide star brightness magnitudes can range from -0.8 to beyond 8.2, though in any one frame, the brightness ratio of the brightest to the. dimmest stars tracked has to be within 2.5 magnitudes of each other, or a 10:1 brightness range, or the CCD pixel wells will saturate on bright stars if the threshold level-integration time is set to acquire dim stars.

The computer software repeats this scanning procedure using the next lower threshold level and its associated longer

Table 1. ASTROS Star Tracker Characteristics and Performance

Parameter	Characteristic or Performance
Aperture	100 mm
Focal Length	250mm
Field of View	2.2 x 3.5 Degrees
Stellar Sensitivity	-0.8 to> 8.2 Mv
Sensor	RCA SID 501 CCD
Format	512 x 320 Pixels
Pixel Size	30 μm Square (24.7x 24.7 arc sec.)
Update Rate	1 Hz Nominal
Number of Stars Tracked	Up to 3
Noise Equivalent Angle	0.3 arc sec. 1σ (Brightest star in FOV)
X-Y Axis Accuracy	0.5 arc sec. 1σ
Roll Axis Accuracy	Not Applicable
Smallest Sensed Position Movement	0.02 Pixel
Mass	44 Kg
Power	54 W (Excluding Heaters)
Lifetime	Not Applicable

integration times permits acquisition of the brightest stars in the field of view. The coordinates of the three brightest guide stars are stored and the optimum integration time. Repeated use of this function with varying threshold levels and integration time is determined by the computer.

The measured positions of the guide stars are displayed on the AST field of view monitors in the Mission operations Control Center and in the Shuttle. A "Starview" program displays the programmed star field around the desired astronomical target on the same monitor as the guide stars. Using manual controls, the astronaut moves the IPS so that the two displays, one actual and one programmed, are coincident, achieving final target acquisition.

To track, the AST computer locates a 5x5 pixel window around each guide star in its field of view. Figure 1, shows how the field of view scanning is done to maximize the signal-to-noise ratio of the star position measurement.

The star centroid-finding algorithm, together with high performance optics and a uniform CCD, are very important in achieving the high accuracy of the AST. A number of algorithms were considered for implementation[4]. A linear centroid algorithm approach with an additive correction term based on sub-pixel position was chosen because of its accuracy and ease of implementation in assembly code. The algorithm* is implemented with two one-dimensional first-moment computations that yield x and y centroid estimates, which are then corrected for the image shape by functions f(x) and g(y). For each star tracked, a 5x5 pixel window of intensity values S(I,J), centered approximately on the star image, is digitized and stored. A back-ground value, B, the average of the ten lowest pixel values on the edge of the window, is subtracted from each pixel value:

$$D(I,J) = \max[S(I,J) - B, 0] \qquad (1)$$

*The algorithm described here was developed by James W. Alexander of JPL. Its description is taken from "Optical Tracking Using Charge-Coupled Devices," Optical Engineering 26(9) 930-938 (Sept. 1987).

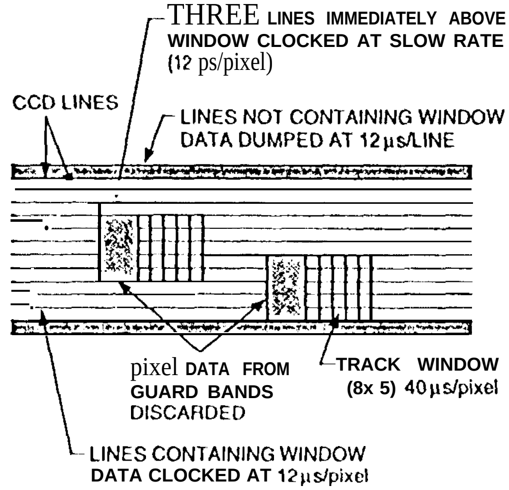

Figure 1. AST Track Windows. While tracking stars, only three 5x5 pixel windows of CCD data are converted and stored. To stabilize the video output, the fast scanning is halted three pixels before the window is encountered (guard bands).

The uncorrected centroid position (x,y) is calculated by:

$$W = \sum_{J} \sum_{I} D(I,J), \qquad (2)$$

$$x = \frac{1}{W} \sum_{J} I \sum_{I} D(I,J), \qquad (3)$$

$$y = \frac{1}{W} \sum_{J} J \sum_{I} D(I,J), \qquad (4)$$

I = column number = x coordinate
J = line number = y coordinate
S = intensity value of a pixel
B = background intensity or threshold level
D = intensity value of a pixel above the background or threshold level
W = sum of the net intensities in the measurement array

where x and y are measured from the center of the **5x5** array. Since the actual distribution of light within the focused star image differs from the ideal due to imperfect optics, a linear motion of a star across a single pixel will produce, in general, a nonlinear centroid output from Equations (3) and (4), such as illustrated in Figure 2. These non-linearities, in

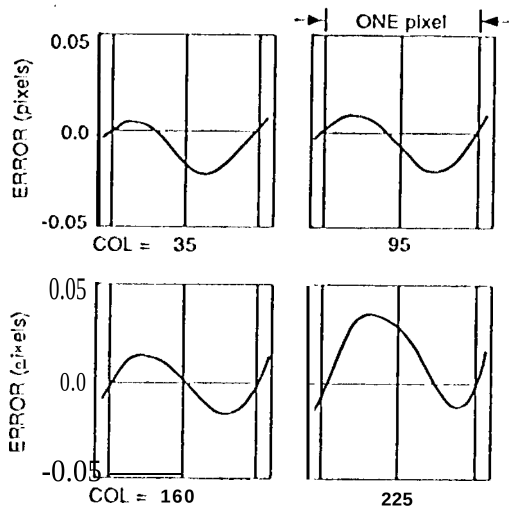

Figure 2. Centroid Deviations. Typical deviations of the uncorrected centroid from linearity for several column coordinates on a single line across the CCD. These error functions, sampled at 16 discrete points across the pixel, become the correction term f(x) in Eq. (5).

principle, can be eliminated by subtracting one dimensional correction functions, f and g, in the form:

$$x' = x - f(x), \qquad y' = y - g(y). \tag{5}$$

Functions f and g were obtained by performing extensive calibration. The calibration showed that f(x) and g(y) vary slowly over the field as the image shape varies and that they have magnitudes of less than 1/20 pixel.

The AST and its unique computer software were a successful pioneering effort. The performance on the Astro- 1 and Astro-2 Shuttle flights completely validated the use of CCDs as the star tracker sensor of choice. Tracking on star fields of up to three stars proved more accurate than tracking on a single star. The use of selectable magnitude thresholds and integration times allowed separating trackable stars from all of the stars imaged in tile field of view, allowed tracking stars over a very large magnitude range, and gave the AST tremendous freedom to find stars no matter where it was pointing. in the (racking mode, the use of tracking windows allowed faster image readout times with tracking errors less than 0.5 arc sec 1 σ, equivalent to 0.02 pixel.

6. STELLAR REFERENCE UNIT (SRU)

This star field tracker provides the prime attitude information for the Cassini mission to Saturn, due to be launched in October 1997. Using a central spacecraft computer which controls the SRU and other spacecraft devices and functions, a program which does star magnitude thresholding to limit the sensed field of view to the brightest stars, and using tracking widows and centroiding, the SRU and its computer software perform autonomous star identification over the entire celestial sphere and provide a three-axis attitude reference to the Cassini spacecraft. The SRU was designed and built by Officine Galileo of Florence, Italy, under a contract with JPL. The SRU characteristics and performance. requirements are shown in Table 2. A good description of the Cassini SRU tracking and identification architecture and of its performance test results are given in the references [5,6].

The design requirements for the SRU were low mass, low power, and functional capability--to autonomously acquire and recognize star fields. With a 15 degree full cone angle field of view to encompass a reasonably-sizcct star field for recognition, a smaller aperture was needed to ensure sensitivity sufficient to track stars at visual magnitudes of 6.05 or brighter and guarantee that at least two stars that can be used for full measurement performance will always be in the field of view.

The SRU is, basically, a commandable star camera that provides raw pixel data to the central spacecraft computer. Special software is required to convert the pixel data into star positions. Since the SRU is not on a manned platform, like the ASI" when it flies on the Shuttle, it must identify its pointing direction without human intervention. To do this initially, after spacecraft separation from the Titan IV/Centaur launch vehicle, an attitude initialization mode is used. A spacecraft sun tracker provides a known reference axis. After the sun tracker acquires the sun, **the** SRU must only recognize star

Table 2. SRU Characteristics and Performance Requirements

Parameter	Characteristic or Performance
Aperture	26.13mm
Focal Length	46.0mm
Field of View	15 Degrees Full Cone Angle
Stellar Sensitivity	>6 Mv
Sensor	Loral Cassini, 3 phase CCD
Format	1024 x 1024 Pixels
Pixel Size	12 p m Square (54.3 x 54.3 arc sec.)
Update Rate	2104 }17. (commandable)
Number of Stars Tracked	LJp(05
Noise Equivalent Angie	<2 arc sec. 10 (Dimmer stars in FOV)
X-Y Axis Accuracy	4 arc sec. 1σ
Roll Axis Accuracy	70 arc sec. 1σ
Smallest Sensed Position Movement	0.1 Pixel
Mass	< 10 Kg
Power	< 12 W
Lifetime	12 years in space & 21/2 years testing

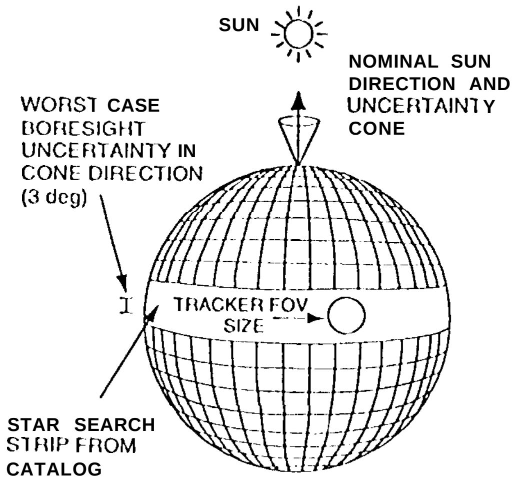

Figure 3. Star search region

fields in a circular strip, as illustrated in Figure 3. This allows the software in the central computer to compare all circular strip star pairs in the computer memory to sensed pairs, using angle separation between pairs to recognize a star field. The process is as shown in Figure 4.

Once initial star field identification is made, the computer software maintains the attitude position quaternion and rate vectors and the attitude uncertainty throughout the spacecraft trajectory. No longer "lost in space," the spacecraft can be commanded to turn from one star field to another of interest using a minimum of stored star fields and reducing the size and complexity of the star field recognition program. The star catalog, limited to 25,()()0 words, contains star position in J2000 vectors and star color, magnitude, and usability flags. 4000 stars have to be stored in the on-board star catalog.

When the spacecraft is commanded to turn from one star field of interest to another, the software sets up track windows (up to 5) in the locations on the CCD focal plane where the new stars are expected to appear. The size and shape of the track windows are variable and are made larger in the direction where (he pointing uncertainty is greatest. When the turn is made, the stars of the new star field appear somewhere in their respective track windows. A centroiding algorithm accurately locates the star positions and centers the track windows on their enclosed stars. The imaged star positions are compared with the stored catalog of star positions and a delta correction to the pointing direction of the spacecraft is made to bring the two into coincidence.

If during the mission, the attitude uncertainty has become so large that a star field cannot be recognized, the software goes back (o the attitude initialization mode. The sun tracker finds the sun, the spacecraft is rotated so its roll axis is pointed toward the sun, and the SRU recognizes an initialization star field, determining the spacecraft attitude. The spacecraft is then turned to point the SRU at the star field it had missed earlier.

The SRU design takes advantage of current CCD technology. The SRU CCD is fabric ate.d with Multi-Pinned Phase (MPP) technology to reduce dark current generated at the CCD silicon-silicon oxide interface. However, the MPP integration procedure is not compatible with the allow tracking both very dim and very bright stars (though not in the same frame) and achieve the most accurate tracking in either Case.

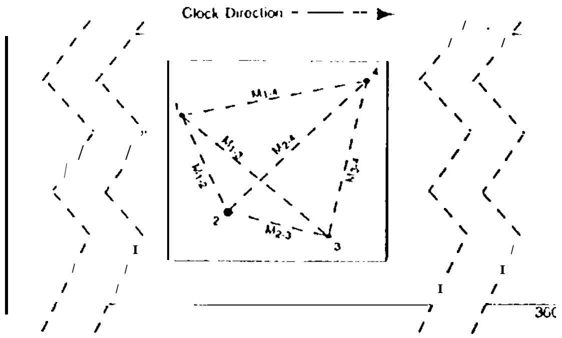

Figure 4. Star Search Region Around Sun Tracker Axis Sunline. Initial Acquisition is done **by the following operations:**

1. Scan SRU field of view. Do star image magnitude thresh olding. output to computer a list of star image pixel locations and magnitudes.

2. Compute distances (angles) between star image pairs: M_{1-2}, M_{1-3}, M_{1-4}, etc.

3 Sequentially order the first star, second star, etc. based on clock angle, from the star catalog.

4. Compute sequentially a set of star pair distances from the first star in the star catalog to all other stars in the catalog that can possibly appear in the field of view.

5. Compare the set of star pair distances from the catalog stars with the star pair distances measured from the field of view star images.

6. If there are not at least three matching stars, repeat the procedure with the next catalog star. Compute the catalog star pair distances and compare with the measured set from the field of view.

7. Eventually, a unique four or more star match is made.

8. Use the celestial sphere coordinates of the matched catalog **stars to determine spacecraft attitude.**

9. Process spacecraft attitude **in computer and command spacecraft to turn to desired attitude from initial attitude . Begin Track Mode.**

The SRU optical system is designed to produce an aberrated point spread function of a star image which has a spot size larger than one pixel (o allow a centroiding algorithm to find the star center.

By using a centroiding algorithm similar to the one described in the ASTROS Star Tracker (AS']'), as w c]] as a more sophisticated version of the track window technique of the AST, star centroid position shifts of 1/10 pixel can be sensed. Total SRU pointing error, including centroiding error, geometric distortion, and noise equivalent angle, is less than 22 μrad (4.5 arc see) 1σ, or 65 μrad (19.5 arc sec) 3σ.

7. ØRSTED ADVANCED STELLAR COMPASS (ASC)

Denmark is developing a geomagnetic research satellite, called Ørsted, to study the Earth's magnetic field and its interactions with the magnetosphere. The science objectives call for accurate absolute measurements of the Earth's magnetic field magnitude and vector components, and the distribution functions of energetic charged particles along the satellite's orbit. To accomplish these objectives, the satellite's attitude must be known continuously to a very high accuracy. To achieve this attitude knowledge accuracy, a star field tracker has been designed and built by a group from the Department of Automation, Technical University of Denmark. Called the Ørsted Advanced Stellar Compass (ASC), it is small, light weight, self-contained with its own microcomputer, and very accurate. 11s characteristics and performance requirements arc shown in '1'able 3.

To initially identify a star field, the ASC is designed 10 process up to **200** star images in its field of view. The ASC images only stars whose signals arc above a threshold level, preset to screen out system and background noise. During development of the star field recognition system,' it was determined that the maximum number of stars available for imaging in any onc possible field of view was approximately 200," given the optical aperture size and the threshold level setting. in the typical field of view about 65 stars would be available for imaging. Therefore, the computer program was

Table 3. ϕrsted ASC Characteristics and Performance

Parameter	Characteristic or Performance
Aperture	23.2111111
Focal Length	16null
Field of View	16 x22 Degrees
Stellar Sensitivity	6 M. or Brighter
Sensor	Sony ICX039BLA CCD
Format	582 x 752 Pixels
Pixel Size	8.3 x 8.6pm (99x 105 arc sec)
Update Rate	1Hz
Number of Stars Tracked	65 Typical
Noise Equivalent Angle	1.2 arc sec. rms, one axis
X-Y Axis Accuracy	1.5 arc sec. rms, one axis
Roll Axis Accuracy	13 arc sec. rms
Smallest Sensed Position Movement	0.1Pixel
Mass	<3Kg including computer
Power	<6W
Lifetime	>1 Year

developed to analyze up to 200 star images and their relationships in any one field of view, if required.

To identify the stars imaged in a field of view, a catalog of the 2200 brightest stars is stored in the ASC microcomputer memory. For each star, its data base entry includes the distances to its two nearest stars and the angle formed between the vector-s from the star to its two nearby neighbors.

To perform initial identification with no a priori knowledge of the attitude of the spacecraft, a star field is imaged and the distances between each imaged star and its two nearest neighbors is computed. obviously, the distance between the two nearest neighbors is available and is computed also. Having computed the distances of the initial star to its two nearest neighbors, and the distance between the neighbors, the three sides of a triangle are known. However, the stars are considered as being located on a sphere, the celestial sphere, and spherical trigonometry is used to find the included angle. Therefore, the angle, A, between the vectors of the initial star 10 its two nearest neighbors is computed using the basic spherical trigonometry law of cosines:

$$\text{Cos } a = \text{Cos } n_1 \text{ Cos } n_2 + \text{Sin } n_1 \text{ Sin } n_2 \text{ CoS } A$$

$$\text{Cos } A = \frac{\text{Cos } a - \text{Cos } n_1 \text{ Cos } n_2}{\text{Sin } n_1 \text{ Sin } n_2}$$

Where the following is measured from the imaged star field, with the ASC at the vertex:

- a = angle from N_1 to N_2
- n_1 = angle from N_2 to A
- n_2 = angle from A to N_1

The geometry is as shown in Figure 5.

For each bright star in the field of view, a search is made in the data base for matching triplet values; distance to neighbor 1, distance to neighbor 2, included angle, to identify the star. With many stars in the field of view, typically 65, there will be enough measured triplets values matching with stored triplet values to positively identify the star field and the coarse attitude of the spacecraft.

Each star has many triplets associated with it to stars other then the two nearest neighbors. if the nearest neighbors are not bright stars and are close to the threshold level, tbey may not be sensed. Therefore, triplets are stored in the database to form triangles such as A-N_1-N_3, A-N_2-N_3, A-N_1-N_4, and A-N_2-N_4, etc. This involves a large data base of approximately 220,000 entries and requires 1.2 megabytes of memory.

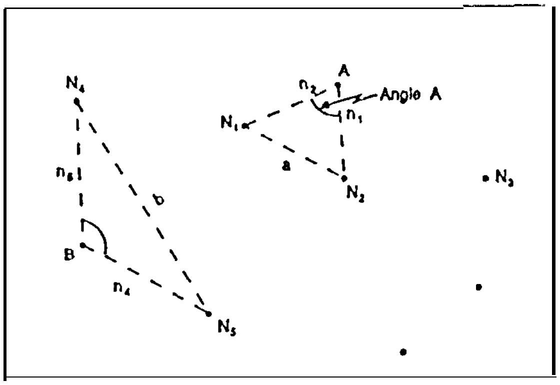

Figure 5. Star Triplet. Stars in the field of view are sensed. In this example, the angles (distances) from star A to its nearest neighbors, N_1 and N_2, are calculated. The angle (distance) between N_1 and N_2., a, is calculated also. Using the spherical trigonometry Cosine Law, the included angle A is calculated. The calculated triplet, n_1, n_2, and angle A, is compared to stored triplet values for a match. In one field of view, there will be many triplets.

once initial acquisition is made and the coarse attitude is known, the ASC program goes into its tracking mode. Tracking involves rotating the spacecraft from the now known initial acquisition attitude to the desired attitude. For tracking, the star catalog holds the right ascension, declination, and magnitude of 11,000 stars. (The 2200 bright stars arc the stars from which the triplets arc generated in the initial acquisition mode). in the tracking mode, the stored positions of the programmed desired stars arc matched to the positions of the imaged stars after spacecraft rotation. 'l-his is clone by a least squares fit. Distance deviations between the corresponding stars arc calculated and the least squares deviation is used, with the known celestial sphere coordinates of the desired star field, to compute the actual attitude of the ASC and the spacecraft. The ASC continues to furnish very accurate attitude knowledge to the Ørsted spacecraft while other devices keep the spacecraft oriented properly, though at less accuracy. The result is a final attitude knowledge accuracy of 1.5 arc scc rms, each axis, and a roll axis accuracy of 13 arc scc rms. Attitude update is available at a 1 Il_2 rate.

8. DISCUSSION

Star field trackers have come a long way since the mid 1980s. Rapidly becoming the attitude sensor of choice, they have taken on a standard configuration: video camera head with CCD sensor and digitized video output, computers for processing the digitized video and furnishing the logic to make the star field tracker function, and software programs to allow determining star field tracker attitude and, therefore, spacecraft attitude. With a solid-state sensor at the focal plane, mostly integrated circuits for the electronics and computer, and no moving parts, star field trackers arc now as reliable as any other electronic instrument on the spacecraft.

Star field trackers have their own unique requirements. in all cases discussed, some kind of thresholding logic is required to limit the stars that arc imaged and whose positions and parameters must be stored in a computer memory. Some algorithm must be used to identify star field relationships, be it pixel distance between many star image pairs, triangles formed by many sets of three star image pairs, or angle between distances from a star image to its two nearby neighbors. Quaternion theory has come into its realm with star field trackers, since coordinate axes must be rotated by computation to find the spacecraft attitude in a desired set of coordinates.

Once tracking, the spacecraft attitude is monitored by the compu tcr program every second or two. If, for some. reason, attitude. information is lost and is no longer being outputted (spacecraft power turned off to clear a fault, or a celestial body in the field of view, etc.) and this condition has not been programmed, the computer program commands the star field tracker to go to the attitude initialization mode, find the. attitude and then cause the spacecraft to be rotated to the desired attitude. '1.bus> autonomous operation using star field trackers, is obtained.

With more computer and memory power available, the trend is to process more and more stars in a field of view to obtain more pointing accuracy. A good rule of thumb is:

$$\text{Error of optical axis attitude} = \frac{\text{Error of single star measurement}}{\sqrt{\text{Number of stars matched}}}$$

Aside from using a large number of stars to match, as the Ørsted Advanced Stellar Compass does, performance can be improved by reducing the error of single star measurements. Here, the tracking windows of the star field trackers used on JPL spacecraft, and the centroiding algorithms used, have shown that these techniques are very effective in helping reduce the total pointing error.

9. PREDICTIONS

Being developed at this time is a type of focal plane sensor called the Active Pixel Sensor (APS)[8,9]. The APS is derived from computer microchip technology and has pixel arrays and pixel photon responses like a CCD. Each pixel, however, has its own readout amplifier, so all of the pixels do not have to be read sequentially. Readout can occur on a desired pixel by pixel basis. Within the next few years, APS devices will be utilized in star field trackers to obtain greater pointing accuracy by spending more time scanning just the pixels with star images and doing more accurate centroiding.

As APS devices develop and allow achieving higher signal to noise ratios, optical apertures will become smaller, since less energy collection is needed. With smaller optics and microcircuit electronics, much of it on the APS pixels, star field trackers and their computers will weigh only a few hundred grams. They will be ideal for controlling the attitudes of small satellites[10].

In conjunction with hardware and sensor development, a large research effort is in progress on developing software for pattern matching and image recognition[11, 12, 13, 14]. At JPL, the Autonomous Feature and Star Tracking (AFAST) program has been going on for several years. Its focus involves developing new image processing algorithms, developing systems of hardware and software to perform pattern and image recognition, and developing testing methods and test beds to verify the performance capabilities of the algorithms and systems being developed. AFAST and similar programs will allow autonomous exploration of planets, asteroids, and other bodies by "recognizing" unique features of these bodies and then taking appropriate programmed action--photography, terrain avoidance, or soil sampling. AFAST is being designed to be used on spacecraft that fly by astronomical objects of interest, and on landers that travel on the surfaces of these objects. For star field trackers, the AFAST research will provide more algorithms and techniques for star field recognition that will make these trackers indispensable for autonomous attitude knowledge and control, and indispensable for autonomous spacecraft scientific exploration. In fact, looking ahead, it appears that the future of star field tracking design and autonomous spacecraft operation belongs to the software engineers.

10. ACKNOWLEDGMENTS

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